



Article Evaluation of the Long-Term Performances of SMA-13 Containing Different Fibers

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Abstract: To clarify the influence of fiber type on the long-term performance of stone mastic asphalt (SMA), this paper used basalt fiber (BF) and lignin fiber (LF) to modify SMA-13 (SMA with aggregate nominal maximum particle size of 13.2 mm) asphalt mixture. The pavement performances (hightemperature performance, cracking resistance at low and medium temperature, and water stability) of the two kinds of fiber-reinforced SMA-13 were checked under different aging degrees (unaged, short-term aged and long-term aged), scanning electron microscope (SEM) test was conducted to explain the strengthening mechanism of the fibers. Fourier transform infrared spectrometry (FTIR) was used to analyze the changes in the chemical composition of asphalt after aging. The results of the wheel tracking test and uniaxial penetration test showed that the high-temperature performance of the BFSMA-13 (defined as the SMA-13 containing BF) is better than that of the LFSMA-13 (defined as the SMA-13 containing LF) at different aging degrees. The high-temperature performance of BFSMA-13 increases with the increase of the aging degree, while the aging process decreases the high-temperature property of LFSMA-13. The results of the three-point bending test and semi-circular bending (SCB) proved that BFSMA-13 is more capable of deformation and less prone to cracking at low and medium temperatures. The results of the immersion Marshal test indicated that BF can better improve the strength and the water stability of the SMA-13 mixture than LF. The SEM images showed that basalt fibers form a solid three-dimensional network structure in the mixture which could contribute to the strengthening of the mixture. The results of infrared spectroscopy analysis showed that styrene–butadiene–styrene (SBS) degrades during asphalt mixture aging, and that the chemical composition of asphalt changes more after aging in LFSMA-13 than in BFSMA-13. The conclusions of this study help toward further understanding of the performance changes of the SMA-13 mixture during its service life and to guide the selection of fiber additives for SMA-13 mixtures.

Keywords: asphalt mixtures; basalt fiber; lignin fiber; SMA; long-term performance

1. Introduction

Stone mastic asphalt (SMA) [1,2] has been widely used in the construction of highways because of its excellent engineering performances. SMA has a high coarse aggregate content that interlocks to form a stone skeleton that resists permanent deformation. The stone skeleton is filled with a mastic of bitumen and filler. It has more stone-on-stone contact and asphalt content than conventional dense graded asphalt mixtures [1,2]. However, with the continuous growth of the logistics industry and traffic load, many asphalt mixtures suffer early damage within 1 to 2 years of service, and in this respect, the durability of the mixtures is gaining increasing attention from the people [3,4]. Thus, researchers hope to further improve the performance of SMA pavement by using various additives [5–7], in which high-quality fiber is an important one.

At present, the common fibers in SMA include plant fiber, polymer synthetic fiber, glass fiber, and so on [8]. Lignin fiber (LF) is the most widely used in SMA [8]. Other



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). similar fibers, such as straw composite fiber [9], bamboo fiber [10], and cellulose fiber [11], were also evaluated for SMA. Such plant fibers could absorb extra free asphalt. However, some researchers argued that the asphalt absorbed by these fibers is just a waste of money because the absorbed asphalt does not contribute to the mixture strength [12]. Additionally, these plant fibers may lose the ability to absorb free asphalt gradually because it could degrade due to the oxidation during the service life [13,14]. Apart from plant fibers, many researchers have studied kinds of polymer synthetic fibers for SMA, such as polyester fiber, polypropylene fiber, and so on [15–17]. They believe that polymer fibers and asphalt are chemically similar and that they can synergize well with the forces. However, some researchers have found that polymer fibers tend to curl at high temperatures, which weakens their function in the mixtures. [9] Additionally, glass fiber is another type of stabilizers used for SMA. Some researchers concluded that fatigue behavior of asphalt concrete reinforced by glass fiber exhibits positive influences [18,19]. Some researchers also found that the brittleness of glass fibers causes it to break easily when mixed with mineral aggregates [20], and the smooth surface of glass fiber leads to poor adhesion with asphalt.

Basalt fiber (BF) is a new kind of inorganic fiber developing in recent years [21,22]. It is made from basalt stone at 1450 °C, and the production process does not produce any harmful by-products. Nowadays, BF has been paid more and more attention in the asphalt pavement engineering due to its excellent technical performance and environmental benefits [23–25]. Liu found that basalt fiber can better improve the performance of SMA-13 mixture than other fibers [26]. Cheng [27] concluded that the addition of basalt fiber is the main reason of improving the mixture performance. Wang [28] found that basalt fiber can effectively reduce the damage degree of asphalt mixture in freeze–thaw cycle test.

Many useful conclusions have been achieved in the study of fresh BF asphalt mixtures. However, more and more attention has been paid to its long-term performance. Although Lee [29], Enieb [30] have evaluated the long-term performance of glass fiber asphalt mixtures, more studies on the effect of different fibers on the long-term performance of SMA are needed. Therefore, this paper focuses on the study on the long-term performances of SMA containing different fibers. BFSMA-13(defined as the SMA-13 containing BF) and LFSMA-13 (defined as the SMA-13 containing BF) were designed for test. The hightemperature performance, low-temperature property, water stability, and anti-cracking ability of mixtures under different aging degrees (unaged, short-erm aged, and long-term aged) were compared and analyzed. SEM tests were adopted to analyze the distribution of BF and LF in the mixture to reveal the strengthening mechanism of the fibers. Since fibers are needed in SMA-13 to stabilize free asphalt [8], hence the SMA-13 without fibers are not manufactured in this study, and LFSMA-13 can be treated as standard SMA-13 in this article. The findings of this study help to further understand the performance changes of SMA-13 mixtures during the service life and to guide the selection of fiber additives for SMA-13 mixtures.

2. Proportion Design of Asphalt Mixture

2.1. Materials

2.1.1. Asphalt and Mineral Aggregates

Styrene–butadiene–styrene (SBS) modified asphalt was used in this paper. The properties were tested according to (*JTG E20-2011*) *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering* [31]. Test results are listed in Table 1.

The coarse and fine aggregate used for test are basalt and limestone respectively, and the filler is limestone powder. the properties of aggregates are listed in Table 2.

2.1.2. Fibers

BF (Figure 1) adopted in this paper is produced by Jiangsu Tianlong Basalt Continuous Fiber Co., Ltd., Yangzhou, China. the length of this short cut basalt fiber is 6 mm. LF (Figure 2) is provided by The JRS company of Germany. LF is flocculent. The properties of BF and LF are listed in Table 3.

| Index | Results | |
|-------------------------------------|---------|--|
| Penetration (0.1 mm) | 71 | |
| Softening point (°C) | 64 | |
| Ductility (cm) | 48 | |
| PI index | 0.5 | |
| Elastic recovery @25 °C (%) | 76 | |
| Rotational viscosity @135 °C (Pa·s) | 2.302 | |
| Relative density @25 °C | 1.021 | |

Table 1. Properties of SBS modified asphalt.

 Table 2. Specific density of aggregates.

| Torres | Bas | salt | Limestone | Filler |
|---|----------|---------|-----------|--------|
| Terms | 10–15 mm | 5–10 mm | 0–3 mm | — |
| Bulk volume specific density (g/cm ³) | 2.856 | 2.851 | 2.687 | _ |
| Apparent specific gravity (g/cm ³) | 2.913 | 2.919 | 2.762 | 2.703 |
| Water absorption (%) | 0.68 | 0.82 | 1.01 | _ |



Figure 1. Basalt fiber.



Figure 2. Lignin fiber.

 Table 3. Properties of basalt fiber and lignin fiber.

| Index | Basalt Fiber | Lignin Fiber |
|--|---------------------|--------------|
| Diameter (µm) | 14 | 8 |
| Density (g/cm ³) | 2.710 | 0.910 |
| Specific surface area (m ² /kg) | 0.15 | 1.93 |
| Hygroscopic rate (%) | 1.63 | 28.70 |
| Heat resistance (°C) | 1550 | 260 |
| Moisture absorption (%) | <0.1 | 12.6 |

2.2. Result of Proportion Design

Marshall method was used to design SMA-13. the content of BF used in the BFSMA-13 was 0.4% by weight of asphalt mixture, and the dosage of LF in the LFSMA-13 was 0.3%. The design results are listed in Tables 4 and 5.

| Mixture Type | Optimal Asphalt-Aggregate Ratio (%) | VV (%) | VMA (%) | VFA (%) | VCAmin | Stability (kN) | Flow Value (mm) |
|--------------|--|--------|-------------|---------|---------------------------|----------------|-----------------|
| BFSMA-13 | 5.8 | 4.2 | 16.7 | 74.9 | 39.3 | 9.8 | 3.0 |
| LFSMA-13 | 6.0 | 4.1 | 17.1 | 76.0 | 39.8 | 8.2 | 2.8 |
| Requirements | / | 3~4.5 | ≥ 16.5 | 70~85 | \leq VCA _{DRC} | ≥ 6 | 2.0~4.0 |

| Sieve (mm | l) | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
|------------------------|--------------|-------|-------|------|------|------|------|------|------|------|-------|
| | Upper limit | 100.0 | 100.0 | 75.0 | 34.0 | 26.0 | 24.0 | 20.0 | 16.0 | 15.0 | 12.0 |
| Percentage passing (%) | Lower limit | 100.0 | 90.0 | 50.0 | 20.0 | 15.0 | 14.0 | 12.0 | 10.0 | 9.0 | 8.0 |
| - | Design value | 100.0 | 95.0 | 62.8 | 27.2 | 22.5 | 19.7 | 16.8 | 14.3 | 12.9 | 11.0 |

Table 5. Aggregate gradation of SMA-13.

3. Test Scope and Methods

In this paper, the effect of fiber types on the performance of SMA under different aged states was explored. First, mixture specimen under different aged states were fabricated. The short-term aged mixtures were used to simulate asphalt mixtures during construction, and the long-term aged mixtures were prepared to simulate asphalt mixtures that have been paved for five to seven years. The aged BFSMA-13 and LFSMA-13 were prepared following the steps provided by AASHTO R30 [32]. Then, the performances of these specimen were checked with several test methods. The wheel tracking test and the uniaxial penetration test were adopted to reveal the deformation resistance of asphalt mixtures. The three-point bending test was used to represent the low-temperature performance of the mixtures. The immersion Marshall test was chosen to reflect the water stability, and the SCB test was conducted to check the cracking resistance (at medium temperature) of the mixtures. The SEM test was used to show the distribution of the fibers in the mixture to reveal the physical structure strengthening mechanism of the fibers. The FTIR test was used to analyze the chemical composition of the asphalt extracted from the asphalt mixture samples under different aging degrees to better explain the effect of the aging process on the chemical composition of the asphalt material used in the mixture. The test plan is shown in Table 6.

Table 6. Test plan.

| Aging Condition | Performance | Method |
|-----------------|------------------------------|---|
| | high-temperature performance | Wheel tracking test, Uniaxial penetration test |
| Unaged | Cracking resistance | Three-point bending test, SCB |
| Ullageu | Water stability | Immersion Marshall test |
| | Functional group analysis | FTIR |
| | Microscopic characteristics | SEM |
| Chart tawa and | high-temperature performance | Wheel tracking test, Uniaxial penetration test |
| Long-term aged, | Cracking resistance | Three-point bending test, SCB |
| | Water stability | Immersion Marshall test |
| | Functional group analysis | FTIR |

3.1. Test Methods for High-Temperature Performance

3.1.1. Wheel Tracking Test

The procedures of the wheel tracking test are in accordance with the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011)* [31]. The size of the test sample is $300 \times 300 \times 50$ mm. The test load is 0.7 Mpa and the test temperature is $60 \,^{\circ}$ C during the test. Dynamic stability (*DS*) is an index to reveal the high temperature performance of the asphalt mixture. The equation of *DS* is shown in Equation (1), where t_1 is 45 min, t_2 is 60 min, d_1 is the rutting depth (mm) at 45 min, d_2 is the rutting depth (mm) at 60 min, N is the rotation speed of the wheel (42 rpm), C_1 , C_2 are the test coefficients and were set as 1.0 in this test. Three specimens were used to determine *DS*.

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2, \tag{1}$$

3.1.2. Uniaxial Penetration Test

The uniaxial penetration test adopted in this paper is specified in the *Specifications* for Design of Highway Asphalt Pavement (JTG D50-2017) [33]. This test is used to reflect the high temperature property of the asphalt mixtures specimen (Figure 3a) of which the shape is a cylinder (the diameter is 150 mm and the height is 100 mm). The load is applied using a metal column (Figure 3b) of which the diameter is 42 mm and the height is 50 mm. The test temperature is 60 °C and the loading velocity is 1 mm/min. The equation of penetration stress σ_p (MPa) and the uniaxial penetration strength τ_0 (MPa) is listed in Equations (2) and (3). *F* (N) is the maximum load, *Ac* (mm²) is the area of the cross section of the metal column and *f* is sample dimension correction coefficient and this *f* is set as 0.350 in this test. Four specimens were used to determine the uniaxial penetration strength.

$$\tau_p = F/A_c, \tag{2}$$

$$\tau_0 = f \times \sigma_p,\tag{3}$$



С

Figure 3. Uniaxial penetration shear test: (a) metal column; (b) experiment photo.

3.2. Test Methods for Cracking Resistance

The three-point bending test and the SCB test was conducted to check the cracking resistance at low and medium temperature respectively.

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3.2.1. Three-Point Bending Test

The steps of the test are contained in the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011)* [31]. The size of the test specimen is $250 \times 30 \times 35$ mm, the test temperature is -10 °C and the loading speed is 50 mm/min. The maximum bending tensile strain when failure is used to describe the low temperature property of the asphalt mixture. The calculation equations of ε_B are listed in Equation (4). Where *L*, and *h* is the span and height of the specimen respectively, *d* is the maximum deflection at midspan. Four specimens were used to determine the bending tensile strain.

$$\varepsilon_B = \frac{6hd}{L^2},\tag{4}$$

3.2.2. SCB Test

The SCB test is conducted according to AASHTO TP 124 [34]. The test temperature is 25 °C. This test is designed according to the Fracture mechanics theory. The cross section of the specimen is semicircle-shaped (the radius is 75 mm), and the specimen is pre-cut for a certain length called pre-cut length (the pre-cut length is 15 mm). The difference between the radius of the specimen and the pre-cut length is called the ductile zone length (DZL). *G*_f is the fracture energy and it is calculated according to Equation (5), where *W*_f is the integral of the load-displacement curve, and *Area*_{*lig*} is the product of the DZL and the thickness of the specimen (t = 50 mm). *FI* index is adopted to reflect the crack propagation rate and it is calculated using Equation (6), where |m| is the absolute value of the slope at the inflection point after the peak of the loading value. *FI* value is negatively correlated with the crack propagation rate. Four specimens were used to determine the *FI*.

$$G_{\rm f} = \frac{W_f}{Area_{lig}} \times 10^6 \tag{5}$$

$$FI = \frac{G_{\rm f}}{|{\rm m}|} \times 0.01 \tag{6}$$

In this paper, fracture toughness (K_{IC}) is also adopted to evaluate the cracking resistance of mixtures. This index is calculated according to AASHTO TP 105 [35], shown as Equation (7).

$$K_{IC} = \frac{P}{2rt} \sqrt{\pi a} Y_{I(0.8)} \tag{7}$$

where: *P* is the applied load (MN); *r* is the specimen radius (m); *t* is the specimen thickness (m); *a* is the notch length (m); $Y_{I(0.8)}$ is the normalized stress intensity factor, calculated with Equation (8).

$$Y_{I(0.8)} = 4.782 - 1.219(a/r) + 0.063 \exp[7.045(a/r)]$$
(8)

3.3. Immersion Marshall Test

The Immersion Marshal test is used to evaluate the water stability of the asphalt mixture. The steps of the test are contained in the *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011)* [31]. Two sets of four specimens were used to determine the Marshall residual stability MS_0 (%). This index is adopted to represent the water stability of asphalt mixture. The equation of MS_0 is shown in Equation (9), where MS is the normal Marshall stability and MS_1 is the Marshall stability of the specimen after being immersed into water for 48 h at 60 °C.

$$MS_0 = \frac{MS_1}{MS} \times 100 \tag{9}$$

3.4. SEM Test

The SEM tests were conducted using the scanning electron microscope produced by Carl Zeiss Microscopy GmbH, Oberkochen, Germany. The test samples were plated by gold using the vacuum coating machine and then been observed by the SEM. SEM images were adopted to analyze the strengthening mechanism of the fibers in the mixtures.

3.5. FTIR Test

The Fourier transform infrared spectrometer (FTIR) adopted in this paper is made by Perkinelmer Instruments Co., Ltd., Shanghai branch, Shanghai, China. The asphalt in the SMA-13 mixtures under different aging degrees was extracted from the mixtures using the vacuum extractor (the medium is trichloroethylene) and tested using the FTIR to find the changing pattern of the chemical functional group in the asphalt to better explain the effect of the aging degree on the chemical composition of the asphalt used in the mixtures.

4. Results and Discussion

4.1. High-Temperature Performance

The results of the wheel tracking test and uniaxial penetration test are presented in Figures 4 and 5 respectively.



Figure 4. Results of dynamic stability.



Figure 5. Results of uniaxial penetration strength.

It can be seen from Figures 4 and 5 that the overall change pattern of the dynamic stability and the uniaxial penetration strength is the same. The high-temperature performance of the BFSMA-13 is better than that of the LFSMA-13 at different aging degrees. The dynamic stability and the uniaxial penetration strength of the unaged BFSMA-13 are 25% and 30% higher than those of the unaged LFSMA-13. After being short-term aged, the dynamic stability and the uniaxial penetration strength of BFSMA-13 are 52.4% and 64.7% higher than those of the LFSMA-13. The corresponding indexes of the long-term aged BFSMA-13 are 68.4% and 92.4% higher than the LFSMA-13. When the aging degree increases, the difference of the high-temperature performances between BFSMA-13 and LFSMA-13 increase.

The high temperature performance of BFSMA-13 increase with the increase of the aging degree, while the aging process decrease the high temperature property of LFSMA-13. After being short term aged and long term aged, the dynamic stability of BFSMA-13 increase by about 14.29% and 22.46% than the unaged BFSMA-13. The decrease extent of the uniaxial penetration strength of the short term aged and long term aged LFSMA-13 are 5.56% and 12.22% respectively.

This is because there are two phenomena in the aging process of asphalt mixtures [36–38]. One is the degradation of the SBS modifier, making the properties of the SBS modified asphalt approach to that of pure asphalt. The other is the aging of the asphalt binder, making it stiffer. In LFSMA-13, the deeper the aging of the asphalt mixture, the more severe the SBS degradation, resulting in a continuous decline in the high-temperature performance of the asphalt mixtures. In BFSMA-13, although SBS degradation will also lead to the decline of high-temperature performance of asphalt mixture, the basalt fibers can synergize better with the stiffer binder, which eventually leads to an increase in the high-temperature performance of the asphalt mixtures. We found that lignin fiber and basalt fiber play different roles in the asphalt mixture. The flocculent lignin fiber can only absorb extra asphalt, while short-cut basalt fiber can cooperate with asphalt mixture to resist the load.

4.2. Cracking Resistance

4.2.1. Cracking Resistance at Low Temperature

The results of the three-point bending test are presented in Figure 6.



Figure 6. Maximum bending tensile strain.

As is shown in Figure 6, the maximum bending tensile strain decreases when the aging degree increases. In the aging process, the light component of the asphalt binder volatilizes, resulting in the hardening and brittleness of the asphalt binder and the decrease

of deformation resistance of the asphalt material [39]. It can be also observed from Figure 6 is that the maximum bending tensile strain of BFSMA-13 is greater than that of the LFSMA-13. The maximum bending tensile strain of the short-term aged and long-term aged BFSMA-13 is 8.04% and 13.83% lower than those of the unaged BFSMA-13. The corresponding decreasing percentage of the short-term aged and long-term aged LFSMA-13 is 13.45% and 22.41% respectively. Greater bending strain means asphalt mixtures are more capable of deformation and less prone to cracking at low temperatures.

As is shown in Table 4, the optimal asphalt-aggregate ratio of BFSMA-13 and LFSMA-13 is 5.8% and 6.0% respectively. Normally, when the asphalt content is lower, the low-temperature performance of asphalt mixtures is poorer. Yet, the low-temperature anti-deformation ability of BFSMA-13 is better than that of LFSMA-13, which further proves that basalt fiber can better enhance the low-temperature anti-cracking ability of SMA-13 than lignin fiber.

4.2.2. Cracking Resistance at Medium Temperature

The results of SCB test is presented in Figures 7 and 8. The two figures show FI and K_{IC} respectively.



Figure 7. Result of FI.



Figure 8. Result of K_{IC}.

As is shown in Figure 7, the FI decreases with the aging degree of asphalt mixtures. This is because the aging process makes the asphalt more brittle, leading to the rapid propagation of micro cracks to macro cracks. On the other hand, the FI of BFSMA-13 is higher than that of LFSMA-13, indicating that the crack propagation rate of BFSMA-13 is lower than that of LFSMA-13 at different aging degrees. The FI of BFSMA-13 is 91.1%, 110.6% and 50.7% higher than that of LFSMA-13 in unaged, short-term aged and long-term aged stages, respectively. This is mainly because that the fracture strength of basalt fiber is bigger than that of lignin fiber and it can disperse some part of the stress [40]. Therefore, basalt fiber can better reinforce the anti-cracking ability than lignin fiber when it comes to the fracture energy and the crack propagation rate.

From Figure 8, it can be seen that the K_{IC} of BFSMA-13 increases with aging process, while that of LFSMA-13 is just the opposite. Additionally, The K_{IC} of BFSMA-13 is greater than that of LFSMA-13. The K_{IC} of BFSMA-13 is 11.5%, 20.7%, and 32.4% greater than that of LFSMA-13 in the unaged, short-term aged, and long-term aged stages, respectively. According to the theory of fracture mechanics, K_{IC} is proportional to the cracking resistance of the material. Therefore, it can be argued that the cracking resistance of BFSMA-13 is better than that of LFSMA-13.

4.3. Water Stability

The results of immersion Marshall test is presented in Table 7.

| Mixture Type | Aging Degree | Marshall Stability (kN) | Immersed Marshall Stability (kN) | Residual Marshall Stability (%) |
|--------------|-----------------|-------------------------|-------------------------------------|------------------------------------|
| | Unaged | 12.12 | 11.01 | 90.84 |
| BFSMA-13 | Short term aged | 12.62 | 11.38 | 90.17 |
| | Long term aged | 12.94 | 11.43 | 88.33 |
| | Unaged | 10.21 | 9.2 | 90.11 |
| LFSMA-13 | Short term aged | 9.94 | 8.83 | 88.83 |
| | Long term aged | 9.88 | 8.56 | 87.24 |

Table 7. Water stability indexes.

It can be seen from Table 7 that the residual Marshall stability of the BFSMA-13 is slightly higher. The residual Marshall stability of the short-term aged and the long-term aged BFSMA-13 decrease by 0.74% and 2.76% respectively compared with that of the unaged BFSMA-13. The corresponding decreasing percentages of LFSMA-13 are 1.42% and 3.18%. Therefore, the effect of the aging degree on the water stability of LFSMA-13 is more obvious. When the aging degree increase, the Marshall stability and immersed Marshall stability of BFSMA-13 increase, and the two indexes of LFSMA-13 decrease. This phenomenon is consistent with the test results of the high-temperature performance.

In the field asphalt pavement, the water damage of asphalt mixtures is not only related to water but also related to the driving speed or other kinds of loads applied on it. The asphalt mixture will generate some micro-cracks when the loading is applied, and then, when the water goes into the mixture, it will further result in water damage. The above test results show that the Marshall stability, immersed Marshall stability, and the residual Marshall stability of BFSMA-13 are all better than those of the LFSMA-13, which means that basalt fiber can better enhance the strength and the water stability of SMA-13 mixture.

4.4. SEM Test Result

The micro images of basalt fiber and lignin fiber are shown in Figure 9, and the micro images of fiber-reinforced mixtures are shown in Figure 10.



Figure 9. SEM images of fibers: (a) basalt fiber; (b) lignin fiber.



Figure 10. SEM images of fiber reinforced mixtures: (a) BFSMA-13; (b) LFSMA-13.

As can be observed in Figure 9, basalt fibers are rod-shaped and have a smoother surface. Lignin fibers, on the other hand, are curled and interwoven and have a rougher surface, which results in a much larger specific surface area than basalt fibers. The microscopic morphology of basalt and lignin fibers determines that they have different roles in asphalt mixtures; the role of lignin fibers in SMA is to absorb excess free asphalt. Although the asphalt-absorption capacity of basalt fibers is not as good as that of lignin fibers, their larger modulus of elasticity allows basalt fibers to better transfer the stresses in the mixture, thus improving the strength and toughness of the asphalt mixture.

As shown in Figure 10, the basalt fibers can form a three-dimensional structure in the mixture [41]. The basalt fibers interweave with each other, however, the fiber itself does not curl (as is presented in Figure 10a). The three-dimensional structure formed by the basalt fibers produces stress caused by the traffic load that is spread more effectively in the mixture, and this structure enhances the weak area (uneven parts formed in the paving process). Lignin fibers also form a three-dimensional structure in the mixture, yet, this structure mainly contributes to the lignin fiber absorbing the asphalt in mixtures. The ability of lignin fiber to bear some of the stress in the mixture is weak because the fracture strength of lignin fiber is much lower (as is illustrated in Table 3). Generally, due to the superior physical and chemical properties of basalt fiber, the ability of basalt fiber to enhance the asphalt mixture is better than that of lignin fiber.

4.5. FTIR Test Result

To study the effect of the aging process on the chemical composition of the SBS modified asphalt used in the asphalt mixtures, the SBS modified asphalt in the BFSMA-13 and LFSMA-13 under different aging degrees were extracted using the rotary evaporation asphalt recovery instrument to test the change of the chemical functional group of the SBS modified asphalt, and the extraction medium is trichloroethylene. The FTIR spectrum of the SBS asphalt extracted from the unaged, short term aged and long term aged BFSMA-13 and LFSMA-13 mixtures were listed in Figures 11–13.



Figure 11. FTIR spectrum of asphalt extracted from unaged mixture: (a) BFSMA-13, (b) LFSMA-13.



Figure 12. FTIR spectrum of asphalt extracted from short-term aged mixture: (a) BFSMA-13, (b) LFSMA-13.



Figure 13. FTIR spectrum of asphalt extracted from long-term aged mixture: (a) BFSMA-13, (b) LFSMA-13.

In Figures 11–13 it can be seen that the FTIR absorption peaks of the extracted SBS modified asphalt are at 2920, 2850, 1700, 1376, 1030, 966 and 698 cm⁻¹, etc. The peaks at 2920 cm⁻¹ and 2850 cm⁻¹ are caused by the antisymmetric stretching vibration and symmetric stretching vibration of methylene (CH2) separately. The peak at 1700 cm⁻¹ is caused by the carbonyl and the peak area of carbonyl or the carbonyl index (CI) can be adopted to evaluate the aging situation of asphalt [42]. The peak at 1376 cm⁻¹ is formed by a specific vibration of methyl (CH3). The peak at 1030 cm⁻¹ is the characteristic peck of the sulfoxide [43], and it can also be used to describe the aging degree of asphalt. The peaks at 966 cm⁻¹ and 698 cm⁻¹ are special peaks of the SBS modified asphalt, and are caused by the butadiene and styrene respectively [44]. The peak areas at 1700, 1376, 1030, 966 and 698 cm⁻¹ were chosen to study the property change of the SBS modified asphalt extracted from the mixtures, because these peaks can reflect the aging degree of the asphalt and the change of some special component of the SBS modified asphalt (butadiene and styrene). The peak areas are calculated using OMNIC software and are shown in Table 8.

Table 8. Characteristic peak areas of SBS modified extracted from mixtures.

| Wave Number | Mixture | $1700 \ {\rm cm}^{-1}$ | $1376 \ {\rm cm}^{-1}$ | $1030 \ {\rm cm}^{-1}$ | 966 cm ⁻¹ | 698 cm ⁻¹ |
|-----------------------------|----------|------------------------|------------------------|------------------------|----------------------|----------------------|
| Peak area (unaged) | BFSMA-13 | 10.994 | 146.239 | 195.657 | 33.376 | 29.939 |
| | LFSMA-13 | 6.236 | 145.334 | 129.157 | 34.395 | 24.767 |
| Peak area (short term aged) | BFSMA-13 | 11.464 | 148.064 | 226.468 | 29.242 | 29.640 |
| | LFSMA-13 | 7.997 | 134.164 | 167.747 | 28.416 | 23.093 |
| Peak area (long term aged) | BFSMA-13 | 15.855 | 148.208 | 242.961 | 26.392 | 26.723 |
| | LFSMA-13 | 26.378 | 119.484 | 184.640 | 27.330 | 22.754 |

It can be seen from Table 8 that when the aging degree increases, the peak areas at 1700 and 1030 cm⁻¹ in the spectrum of the SBSBF (defined as the SBS modified asphalt extracted from BFSMA-13) increase, and the peak areas at 966 and 698 cm⁻¹ decreases. It shows the same change pattern in the spectrum of the SBSLF (defined as the SBS modified asphalt extracted from LFSMA-13). The peak area at 1376 cm⁻¹ is stable because there is almost no change with the increase of the aging degree at this peak. This means that the aging process increases the amount of carbonyl and sulfoxide in the asphalt and decreases the amount of the butadiene and styrene in the SBS modified asphalt. This phenomenon is worth of being paid attentions, because in further studies, the properties of the asphalt mixtures paved on the road can be estimated by conducting the FTIR test on the SBS modified asphalt extracted from the asphalt. However, this will only be reasonable when the number of testing samples is enough. Thus, this paper just analyzed the change of the chemical functional groups in the SBS modified asphalt extracted from the mixture samples.

The peak areas at 1030 cm⁻¹ in the spectrum of SBSBF are bigger than that in the spectrum of SBSLF at all the aging degrees, and the peak areas at 1700 cm^{-1} in the spectrum of SBSBF is higher than that in the spectrum of SBSLF under the unaged and the short-term aged situation. This means that overall, the aging degree of the asphalt in BFSMA-13 is bigger than that of the asphalt in LFSMA-13. This is mainly because, in the LFSMA-13, the asphalt content (6.0%) is bigger than that of the BFSMA-13 (5.8%). However, the increasing percentage of the peak areas at 1030 and 1700 cm⁻¹ in the spectrum of SBSBF is lower than those in the SBSLF. The peak area at 1030 cm^{-1} in the spectrum of short-term aged and long-term aged SBSBF is 15.75% and 24.18% higher than that of the unaged SBSBF. The corresponding increasing percentage of the SBSLF indexes is 29.88% and 42.96%. The peak area at 1700 cm^{-1} in the spectrum of short-term aged and long-term aged SBSBF is 4.28% and 44.22% higher than that of the unaged SBSBF. The corresponding increasing percentage of the SBSLF indexes is 28.24% and 323.00%. Therefore, the aging process has a higher impact on the chemical composition of SBSLF than the SBSBF. This is mainly because that the lignin fiber is a kind of plant fiber and it could degrade in the aging process, because lignin fiber is a kind of plant fiber and asphalt is a weak acid material [45].

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In the manufacturing process (chemical treatment) of lignin fiber, the surface of lignin fiber has many polar groups like carboxyl groups and phenolic hydroxyl groups [46], these polar groups might make the lignin fiber and the asphalt interact with each other more in the aging process and make the lignin fiber degrade.

5. Conclusions and Suggestions

In this paper, the long-term performance of SMA-13 containing different fibers was compared. The following conclusions can be drawn after conducting this research:

- (1) The high-temperature performance of the BFSMA-13 is better than that of the LFSMA-13 at different aging degrees. The high-temperature performance of BFSMA-13 increases with the increase of the aging degree, while the aging process decreases the high-temperature property of LFSMA-13.
- (2) The cracking resistance of BFSMA-13 is better than that of LFSMA-13 at different aging stages. The test results proved that BFSMA-13 is more capable of deformation and less prone to cracking at low and medium temperatures.
- (3) The Marshall stability, immersed Marshall stability, and the residual Marshall stability of BFSMA-13 are greater than that of LFSMA-13, which shows that basalt fiber can better improve the strength and the water stability of SMA-13 mixture than lignin fiber.
- (4) Different properties of BF and LF lead to their different roles in the mixture. BF can improve the performance of asphalt mixtures by acting in concert with the asphalt mixture. LF can absorb excess free asphalt in SMA-13, and it is not as good as BF in improving the performance of the mixture.
- (5) At the characteristic peak, the increasing percentage of the peak areas in the spectrum of SBSBF is lower than those in the SBSLF as the mixture ages, indicating that the aging process has a greater impact on the chemical composition of SBSLF than the SBSBF.

Some suggestions are made for further works: (1) the aging method used in this paper only involves thermal aging, and other aging conditions should be adopted, such as ultraviolet light aging; (2) the fatigue properties of asphalt mixtures were not tested in this paper and should be conducted in the future; (3) properties of fiber asphalt mastic at different aging conditions should be tested in further studies; and (4) the reinforcement mechanism of fiber on asphalt mixtures needs to be further clarified.

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